FINAL REPORT

Title: Effects of fuels treatments on reduction of fire risk and restoration of oak-pine forests in Central Hardwood Forest landscapes

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List of Abbreviations/Acronyms

CS	Central States variant of Forest Vegetation Simulator
DBH	diameter at breast height
DWD	downed woody debris
FFE	Fire and Fuels Extension
FIA	Forest Inventory and Analysis
FVS	Forest Vegetation Simulator
FVS-FFE	Forest Vegetation Simulator Fire and Fuels Extension
JFS	prior Joint Fire Science Program study
P3	Forest Inventory and Analysis Phase 3 sample
SN	Southern States variant of Forest Vegetation Simulator

Keywords

Pinus echinata, *Quercus*, woodland, ecological restoration, modeling, landscape scale, LANDIS PRO, forest vegetation simulator, Fire and Fuels Extension, Forest Inventory and Analysis, Ozarks, fuel loading

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Abstract

This project had a site-scale component and a landscape-scale component. In the site-scale component, we tested whether the default model of the Forest Vegetation Simulator – Fire and Fuels Extension (FVS-FFE) fuel loading values from two variants (Central States and Southern variants) were representative of field-based fuel loads using Forest Inventory and Analysis (FIA) data collected in the Ozark Highland region. We also compared fuel loads projected by FVS-FFE to empirical data collected from a 14-year study examining the impact of harvesting and burning on fuel loading in the Missouri Ozarks. Results suggest that the choice of variant had little impact on short-term projections but using observed fuel values rather than defaults can improve short-term projection accuracy. We used the site-scale results to parameterize reductions in fine and coarse fuels due to a one-time prescribed burn in the modeling simulations for the landscape-scale component. Six scenarios were modeled using the LANDIS PRO forest landscape model: no management, burn only, harvest only, and a combination of harvest with burns treatments followed by fire-free intervals of differing starting times or durations to facilitate tree recruitment. Thus, we employed an integrated field and modeling approach to address how prescribed burning and harvesting can help restore shortleaf pine-oak woodlands on Missouri Ozark landscapes in the next 100 years. Specifically, we addressed the following questions: (1) Can frequent prescribed burns that mimic the historical fire regime restore pine-oak woodlands over the long-term? (2) Is harvest necessary to restore pine-oak woodland? (3) Do different prescribed burn regimes in combination with harvesting result in landscapes with different compositions of shortleaf pine and oaks? We found that no management and prescribed burn-only scenarios cannot restore current forests to a historical woodland condition, however scenarios including harvest can restore woodland conditions by the late 2020s. When coupled with harvest, prescribed burn regimes affected species composition. Increasing the number of burns increased the basal area and density of shortleaf pine while decreasing that of white oaks.

Objectives

In response to JFSP FON 2014-1 Task 1, Fuels treatment effectiveness across landscapes, our overall objective was to assess fuels treatment effectiveness across Mark Twain National Forests and adjacent Missouri State Forests in the Missouri Ozarks landscape. We used field-based studies from multiple prescribed burn and forest inventory plots to quantify fuel loading in response to forest management, site conditions, and forest composition and structure. Results from field-based data were used to parameterize and validate Forest Vegetation Simulator Fire and Fuels Extension (FVS-FFE) and LANDIS PRO. We then used this modeling approach to determine how fuels treatments can maximize ecological restoration of oak and pine forests and woodlands. We answered two specific questions through simulation:

1) What landscape fuels treatment strategies are most effective at reaching restoration objectives for forest structure and composition?

2) How can landscape fuels treatment strategies maintain effectiveness over the short-term (<20 years), mid-term (20-50 years), and long-term (50-100 years)?

Background

Historical fire regimes in the Central Hardwood landscapes of the eastern United States were characterized by frequent, low-severity surface fires in oak and mixed oak-pine forests punctuated by periodic intense crown fires in pine forests. Such regimes maintained open-canopy shortleaf pine-oak woodlands on xeric sites. Following large-scale harvest and fire suppression, those woodlands grew denser with more continuous canopy cover, and they gained mesic, fire-sensitive species at the expense of shortleaf pine (e.g., red maple; Hanberry et al. 2014). Fire exclusion has also led to hazardous fuel buildups.

There is high interest in restoring shortleaf pine-oak woodlands. Most have been converted to other forest types, but those that remain are valued for high stand-scale and landscape-scale diversity. Prescribed burns in the Missouri Ozarks (Figure 1) reduce fuels and restore forest structure at stand scales (Blake and Schuette 2000). Thus, prescribed fire is proposed as a means to reduce hazardous fuels and restore historical forest composition and structure (Mark Twain National Forest 2005).

Prior stand-scale studies suggest that prescribed burning and harvesting could be effective for restoring pine-oak woodlands. However, previous short-term, stand-scale studies provide little insight into long-term, landscape-scale outcomes. Evaluation of long-term, cumulative effects of fuels treatments remains challenging, particularly at landscape scales. Practical constraints such as large spatial extents, long timeframes, and high costs of field work often make this task difficult using case studies or field experiments. Consequently, comprehensive assessments of fuels treatments on reducing fire risk and restoring oak-pine woodlands across landscapes are rare.

Simulation models in combination with field studies provide a viable method for quantitatively analyzing large-scale, long-term, cumulative effects. The Forest Vegetation simulator (FVS) is a stand-based, individual tree growth and yield model. The Fire and Fuels Extension (FFE) of FVS is designed to simulate changes in fuel loading through time and can incorporate user-specified fuel treatments into projections. Together, FVS-FFE can predict forest stand dynamics and potential fire risk under various fuels treatments (Beukema et al. 1999, Reinhardt and Crookston 2003). Forest landscape models are suitable for modeling cause-effect relationships at broad spatial and temporal scales (Mladenoff 2004). LANDIS PRO is a spatially explicit simulation model of forest landscape change in response to disturbance, succession, and management developed with funding by the National Fire Plan (He et al. 2005, Wang et al. 2013). LANDIS PRO can simulate the effects of landscape-scale fuels treatment prioritization and implement strategically placed treatments where the effects on landscapes extend beyond the area physically treated. Its strength is the ability to predict the effects of interacting disturbances including prescribed fires and wildfires on tree mortality, composition, structure, fuel load, and potential fire risk at landscape scales.

LANDIS PRO simulates ecological dynamics and forest management at large extents over long periods of time. Within each iteration (1 or 10 years), the model simulates: (a) species-level forest succession (i.e., reproduction, establishment, growth and competition among species, and mortality); (b) seed dispersal; (c) fire ignition, spread, intensity and severity; (d) fine and coarse fuel loads, and common fuels treatments such as prescribed burning and mechanical removal, (e) timber harvest and silvicultural treatments, and (f) windthrow and other disturbances such as insects and diseases. Each of these elements affects forest species composition and size structure in each raster cell (Figure 2). The simulated processes interact to model complex outcomes that are tracked across the landscape (e.g., over time windthrow affects fuel, which affects fire severity, which affects tree species composition, which affects harvest patterns, etc.).

Stands are the basic unit for forest management, and LANDIS PRO implements management events by selecting stands for treatment. Management areas are comprised of groups of stands that are managed in a similar way. Fuels treatments are applied in the context of management areas. Each management area may have unique management prescriptions, including single or multiple fuels treatments. LANDIS PRO computes the potential fire risk for each forest stand by evaluating the potential fire intensity and probability of fire occurrence, and selects the stands for treatment based on stand age, fire risk, and adjacency. Each treatment prescription is specified by the proportion of stands to be treated, the rotation and frequency of treatment, and the amount of fine fuel and coarse fuel removed.

We used a combination of field and simulation studies in over 0.6 million ha of public lands of the Missouri Ozarks landscapes to parameterize FVS-FFE and LANDIS PRO and simulate varying configurations of fuels treatments to assess how landscape fuels treatment strategies can most effectively affect intensity, rate of spread, and patterns of severity of subsequent wildfires. Results from this study provide references for fuel management of other Central Hardwood Forest regions.

Materials and Methods

1. Study Area and Sites

Missouri's Ozark Highlands is a 9.4 million ha landscape, representative of the heavily forested Central Hardwoods region (Figure 1). Most of the study area lies in a moderately dissected upland plain associated with the Roubidoux Formation, and average relief is less than 30 m (≈98 ft). Soils are generally loamy to sandy and low in soluble bases such as calcium (Nigh and Schroeder 2002). Climate is humid continental with long hot summers and cool winters. Mean annual temperature is around 13 °C (55 °F) and mean annual precipitation is around 1115 mm (44 in) (Brandt et al. 2014). Historically, fire was an important disturbance to maintain open pine-oak woodlands, however, understory vegetation has become more dense than the historic conditions (Nigh and Schroeder 2002, Guyette and Dey 1997). At the landscape scale, current average basal area is approximately 11 $m^2 ha^{-1}$ (48 $ft^2 ac^{-1}$) and average tree density is approximately 924 trees ha^{-1} (374 trees ac^{-1}) (Jin et al. 2018). Common tree species belong to four major species groups: (1) pine: shortleaf pine (*Pinus echinata* Mill.); (2) white oak group: white oak (*Quercus alba* L.), and post oak (*Q. stellata* Wangenh.); (3) red oak group: black oak (*Q. velutina* Lam.), scarlet oak (*Q. coccinea* Muenchh.), and northern red oak (*Q. rubra* L.); (4) others: sugar maple (*Acer saccharum* Marshall), red maple (*A. rubrum* L.), mockernut hickory (*Carya tomentosa* Sarg.), eastern redcedar (*Juniperus virginiana* L.), and black cherry (*Prunus serotina* Ehrh.).

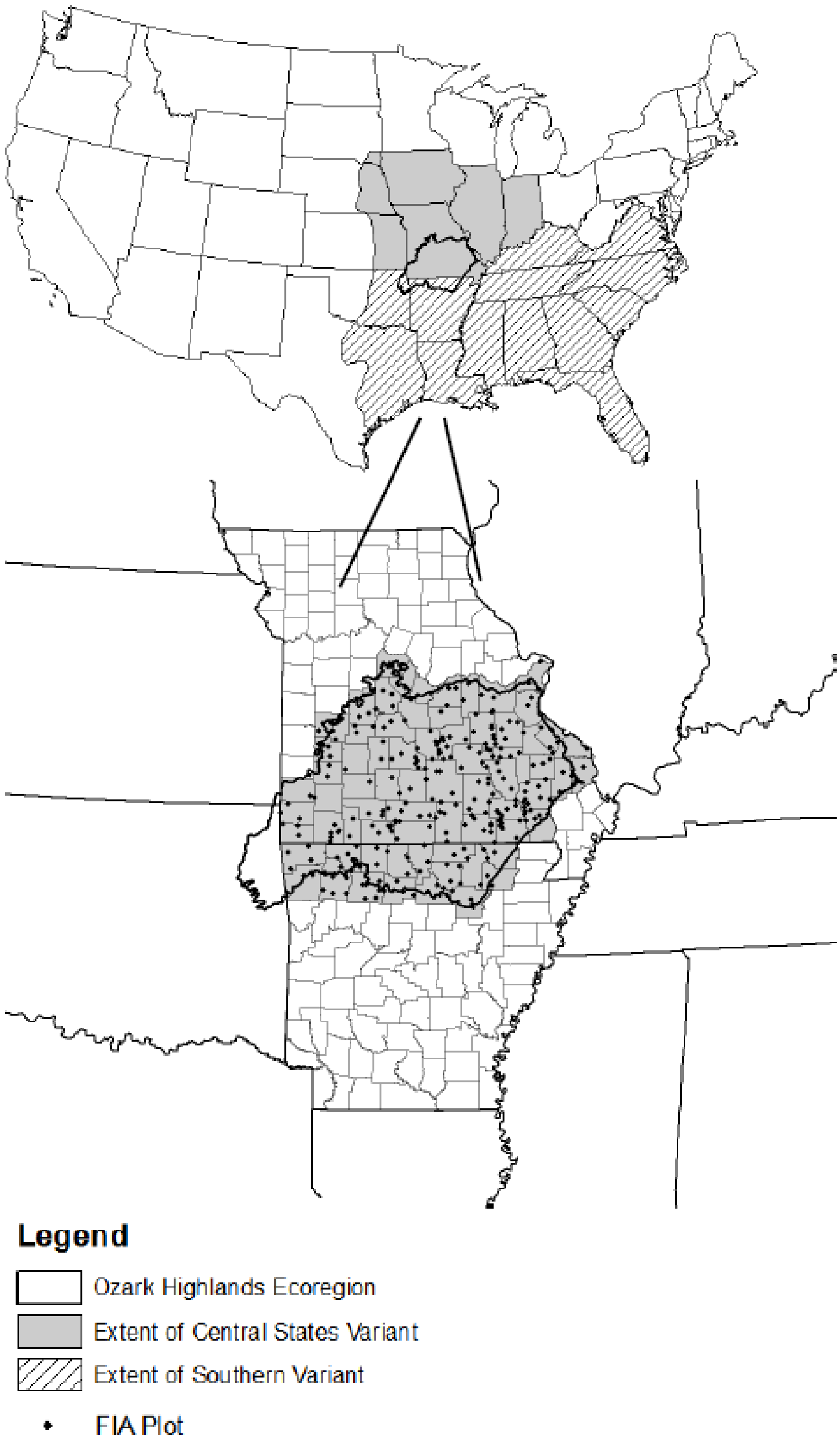

Figure 1. Study area of the Ozarks landscape in Missouri, with approximate locations of Forest Inventory and Analysis plots used for fuel loading validation in FVS-FFE.

2. Site-Scale Study

To validate the accuracy of FVS-FFE default fuel loading values, we used fuel loading information from downed woody debris (DWD) data collected on Forest Inventory and Analysis (FIA) Phase 3 (P3) plots from 2002-2011 in counties in Missouri and Arkansas within the extent of the Ozark Highlands (Bechtold and Patterson 2005). Every 16th FIA field plot was selected for P3 sampling producing a sampling intensity of one plot per 96,000 acres (Figure 1). We restricted our analyses to plots within the oak-pine (400) and oak-hickory (500) forest type-groups, which were the most prevalent throughout the Ozarks. FIA measures DWD using the planar transect method for each timelag class (1000 hour, 100 hour, 10 hour, 1 hour, litter, duff). The accuracy of FVS-FFE default fuel loading values were validated by generating bootstrapped confidence intervals from the FIA data at the forest type-group level. We bootstrapped a distribution of mean fuel loading for each of the 6 fuel classes by randomly selecting a 75% subset of plots and calculating their mean over 5,000 iterations. A 95% confidence interval was then created from the 2.5 and 97.5 percentiles of the bootstrapped distribution, and the FVS-FFE default values were checked for inclusion within the interval.

To examine the accuracy of simulated FVS-FFE fuel loading values for both the Central States (CS) and Southern (SN) variants, empirical data from a prior Joint Fire Science Program study (JFS study) were used to initialize and compare simulation outcomes over 14 years. The JFS study was located in Reynolds County, MO and began in 2002 to examine the effect of harvesting and burning on woodland restoration in the Missouri Ozarks. It used a randomized complete block design that included two different burn treatments, a prescribed burn only and a treatment that combines thinning and burning, as well as a thin only treatment and an untreated control. Each experimental unit was approximately 2 ha (5 ac), and the study was replicated in three blocks. The burn treatments were combined with landscape position (north-facing slopes, ridge-tops, and south-facing slopes) to create six experimental units treated with fire in each block. The harvest treatment occurred in 2002 and reduced overall stocking to 40% (Gingrich 1967). Burns were applied in 2003, 2005, and 2015.

Fuels data were collected using a modified planar intersect method, with fixed-area destructive samples taken at the end of each transect. Transect lines were overlaid on the overstory plots, radiating out from plot center. 1000 hour fuels were measured on a 50 foot transect, 100 hour fuels were measured on a 12 foot transect and 1 and 10 hour fuels were measured on a 6 foot transect. Destructive samples had an area of 2.67 ft^2 and were separated into litter and woody components, which were later dried to a constant weight. Additionally, measurements of litter depth and duff depth were made at 5 foot intervals along the length of the entire transect. The fuel transects were measured pre- and post-treatment in 2002. They were remeasured after the second burn in 2005/2006, and then a third time pre- and post-treatment in 2015. Duff tons/acre values were generated using the depth measurements and a bulk density of 4.84 tons/acre/in from McDaniel (2012).

We input empirical stand data into FVS-FFE to simulate the JFS study treatments and project stand development from pre-treatment through 2015 using a standardized timeline of reporting in all years in which a treatment was applied. Each treatment was simulated with all possible permutations of initial parameters of variant, measured fuels vs prediction/defaults, and weather (for treatments involving burns). Harvest treatments were simulated by thinning from below.

Fuel loading was output at each time step. Prescribed burn treatments were simulated with both default and empirical weather parameters. The empirical data were then used to determine the accuracy of the FVS-FFE model using different management treatments on short and long time scales. We plotted observed vs projected values at the end of the simulation period against a 1:1 line by treatment and fuel category.

To test whether the errors in modeled fuel values were large enough to change the fuel model chosen by FVS-FFE, the fuel model assignments based on modeled values were compared to the fuel model assignments based on empirical data and classified as right or wrong. We used frequency tables to determine if fuel inputs (empirical vs default) weather inputs (empirical vs default), choice of variant (CS vs SN) or study treatment affected fuel model classification. Fisher's Exact Test was used for variant, fuels data, treatment, and weather. Pre-treatment and end of simulation results were tested separately.

3. Landscape-scale studies: FVS-FFE and LANDIS PRO

The Forest Vegetation Simulator Fire and Fuels Extension is a well-established model (Beukema, et al. 1999, Reinhardt and Crookston 2003) that has been widely used to simulate interactions of fire and vegetation and long temporal processes such as the accumulation and decomposition of coarse woody debris, litter, duff, and fallen trees. We used FVS-FFE to process stand input data and predict stand-level effects of specific fuel management. However, FVS-FFE does not simulate landscape processes that affect fire ignition and spread patterns.

The LANDIS PRO fuel module simulates the most common fuel reduction methods, including prescribed burning and mechanical fuel removal (He et al. 2004). Initial fuel loads must be estimated on the landscape. Fine fuel is derived from species-specific age cohorts for each site (based on species composition, age cohorts, and attributes parameterization). Coarse fuel is derived from stand age in combination with disturbance history at each site. We derived fuel load classes for our simulations based on inventory data. For fine fuel loads, we used a combined total of less than 0.5 kg/m^2 of litter (1 kg/m^2 ≈ 4.5 tons/acre), 1- and 10-hour fuels to represent class 1 (low level), and a total of 2 kg/m^2 or more of these same components to represent class 5 (high level) (Shang et al. 2007). Classes 2, 3 and 4 linearly increase from 0.5 to 2 kg/m^2. Coarse fuel class 1 (low) was defined as less than 0.5 kg/m^2 of 100-hour and 1000-hour fuels; class 2 (medium-low) as 0.5 to 0.75 kg/m^2; class 3 (medium) as 0.75 to 1 kg/m^2; class 4 (medium-high) as 1 to 1.25 kg/m^2; and class 5 (high) as 1.25 kg/m^2 or more (Brown 1974, Loomis 1973, Kolaks 2004). Fuel accumulation and decomposition information were generalized from forest inventory data in the Mark Twain National Forests and data from the Missouri Ozark Forest Ecosystem Project (MOFEP) (Shifley and Brookshire 2000, Spetich et al, 1999). Both types of fuel were updated with succession dynamics, disturbance, and treatments each at model iteration.

We used a coupled FVS and LANDIS PRO modeling approach in this study (Figure 2). FVS-FFE simulated plot-scale response of fuels treatments. The simulated responses were used to assist the parameterization of LANDIS PRO fuel module. LANDIS PRO simulates landscape-scale fuels treatment allocation as a combination of forest succession at individual cells. Short-term forest response can be verified by comparing simulated data with field data and mid- to long-term response can be verified by comparing LANDIS PRO predictions with FVS predictions.

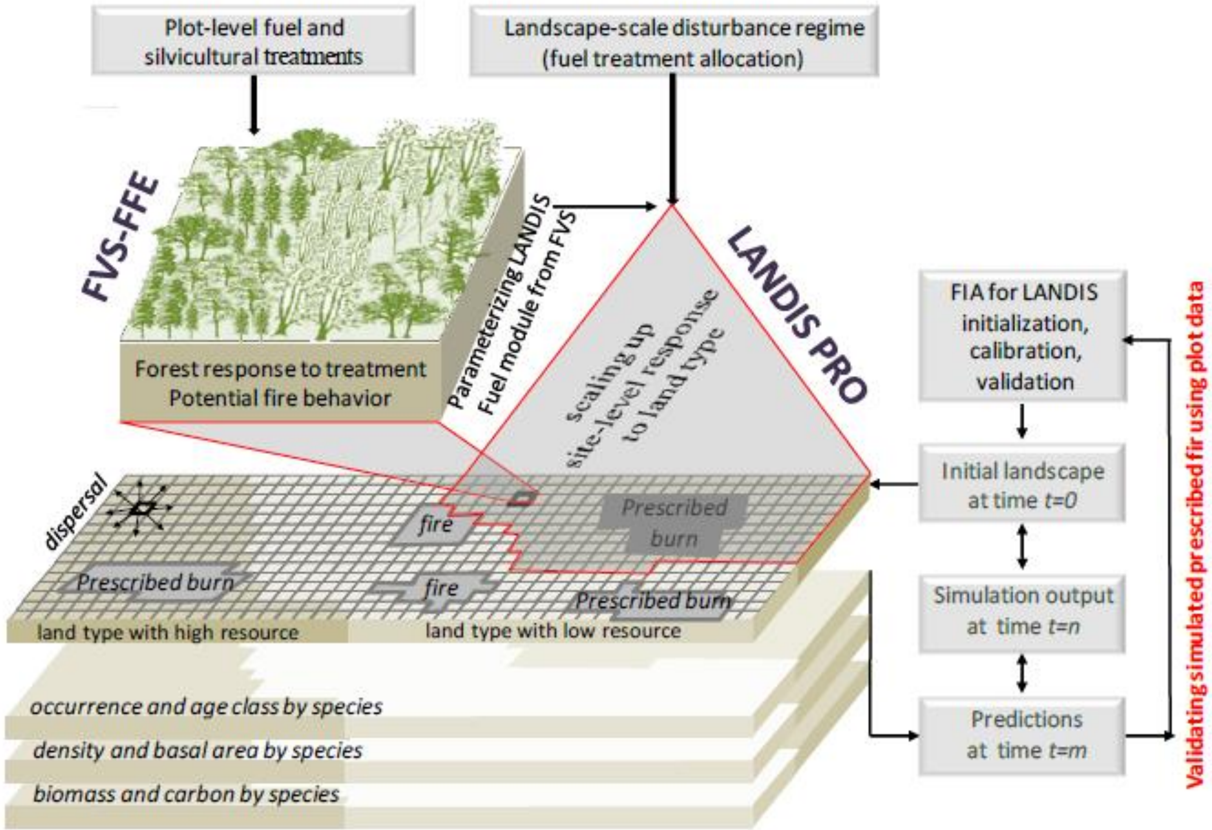

Figure 2. A coupled FVS-FFE and LANDIS PRO modeling approach was used in this study. FVS-FFE simulates plot-scale response of fuels treatments. The simulated responses were used to parametrize the LANDIS PRO fuel module. LANDIS PRO simulates landscape-scale fuels treatment allocation in combination of forest succession at individual cells.

The development of FVS-FFE and LANDIS PRO approaches made it possible to examine the response of fuels treatments on forest composition and structure at landscape scales with a degree of realism and spatial fidelity not attempted before. By utilizing both models we were able to exploit the strengths of each at different spatial and temporal scales. Furthermore, projections that are consistent across models will be more reliable, as multi-model ensembles frequently have greater accuracy than any individual model.

a. Design of Simulation Experiments

Simulation experiments examined a range of harvest and burning treatment alternatives that encompassed current and planned management for the landscape. The six included scenarios were: *no management, burn only, harvest only, harvest-burn (30 yr), harvest-burn (50 yr),* and *harvest-burn (100 yr)*. All simulations were run from 2010 to 2110 under a current climate scenario, with a time step of two years. In the *no management* scenario, forest dynamics were solely dependent on forest growth and succession. In the *burn only* scenario, half the study area was burned in the first two years of simulation; in the next two years, the other half would be burned, and so on. Thus, each stand in the study area was burned every four years throughout the simulation. In the *harvest only* scenario, thinning-from-below was applied to hold basal area between 7 and 16 $m^2\ ha^{-1}$ (≈30-70 $ft^2\ ac^{-1}$). From the beginning of simulation, approximately 1/5th of the total study area was assessed for harvest every two years with harvesting implemented if basal area exceeded 16 $m^2\ ha^{-1}$ (70 $ft^2\ ac^{-1}$). Harvest priorities were assigned to four species groups in a descending order: others (sugar and red maples, mockernut hickory, eastern redcedar, black cherry), red oak group (black, scarlet, and northern red oaks), white oak group (white and post oaks), and shortleaf pine. Within a given group, trees with the smallest diameter at breast height (dbh) would be harvested first. Every 16 years, the same harvest area was evaluated again for harvest using the same criteria mentioned above.

In the burn and harvest combination treatments, we examined three different scenarios. In the *harvest-burn (30 yr)* scenario, stands were burned every 4 years for the first 30 years (2010-2040), then each stand was burned every 20 years to encourage regeneration until the end of the simulation; the harvest regime was the same as the *harvest only* scenario. In the *harvest-burn (50 yr)* scenario, stands were burned every 4 years for the first 50 years (2010-2060), then stands were burned every 20 years until the end of simulation; the harvest regime was the same as the *harvest only* scenario. In the *harvest-burn (100 yr)* scenario, stands were burned every 4 years during the 100-year simulation period; the harvest regime was the same as the *harvest only* scenario. The simulation was conducted five times to identify probable variations in outcome; however, since the variation was extremely low, we only included results from one simulation.

b. Data Analysis

To estimate outcomes of alternative restoration treatments on future species composition and forest structure, we employed an integrated field and modeling approach to simulate effects of prescribed burning and harvesting on the restoration of shortleaf pine-oak woodland composition and structure in the Mark Twain National Forest for a 100-year period. The landscape, 31,000 ha (≈77,000 ac), was jointly identified by several federal and state agencies, as well as conservation groups as a priority area for pine-oak woodland restoration. It contains the highest known concentration of restorable pine-oak woodlands, and known occurrences of species of conservation concern in Mark Twain National Forest.

Simulated variables included basal area and tree density by species group and 10-year age classes. To assess whether each management scenario can restore current forests to a historical woodland condition, percent canopy cover was calculated on simulated basal area and tree density then compared to the historical percent canopy cover (40-80%) of woodlands in the study area (Ladd et al. 2007). Only trees with a dbh larger than 12.7 cm (5 in) were included for percent canopy cover calculation.

c. Model Validation

Model validation in the traditional sense involves using independent data at a given time and space to check against model predictions for that time and space. Model validation for large scale, stochastic models that project long-term future conditions has not been previously done, because the validation data do not typically exist for future conditions. Also, complete historical data do not exist for a large region, which precludes using simulations that start from the past with present data then used for validation. Initial density and age of trees were derived from forest inventory (FIA) data. LANDIS PRO was parameterized using detailed Mark Twain National Forest stand inventory data and the actual prescribed fire and silvicultural treatment plans. Simulations were initialized based on data from 1187 stand plots collected in the early 2010s in the study area. FIA data were used for both calibration and validation using a data splitting approach: 50% of the FIA plots from the 1980s-2010s were used for calibration and the other 505 for short-term model validation. Specifically, tree density, basal area, and above ground carbon density of different species groups were used for calibration and validation. Discrepancies between model predictions and FIA data at the landscape scale were relatively small: both mean error and root mean squared error were <10%. Model predictions of mortality rates were similar to those of field studies in the study area (Kinkead 2013). Specifically, average mortality rates after a single burn from model prediction and field studies of trees with diameter at breast height less than 12 cm were 37% and 44%, respectively. Average mortality rates from model predictions and field studies of trees with diameter at breast height greater than 12 cm were 10% and 15%, respectively.

Results and Discussion

Site-scale study:

FVS-FFE default surface fuel loading values were largely unrepresentative of FIA inventoried fuel loading in the Ozark region (Figure 3). For the oak-hickory group, the CS variant default values for 1 hour, 100 hour, and litter classes were included in the inventory confidence intervals. For the SN variant, only the defaults for the 1 hour and 1000 hour classes were included in the inventory confidence intervals. In the pine-oak group, none of the CS variant defaults were included in the confidence intervals. The SN variant defaults for 1000 hour and litter classes were included in pine-oak group confidence intervals. In cases where default values were not within the inventoried range, both the CS and SN variant values tended to be greater than the inventoried range. The only situation where both variants were inside the bounds of the confidence interval was for 1 hour fuels in the oak-hickory group. The default values were found to be directionally similar, as there were no cases in which one variant was higher than the observed range while the other was below. The values were consistently greater than the observed range with the exception of the litter class in the oak-hickory forest-type.

We found that most discrepancies in initial fuel loading values had little effect on model function because FVS-FFE aggregates fuel loading values into coarsely defined fuel-model groups based on the aggregated tons/acre of all small diameter fuels (0-3”) and large diameter fuels (≥ 3”). When we compared FVS-FFE simulations on empirical data to empirical results, the initial fuel model selected by FVS-FFE was almost always classified correctly (Figure 4).

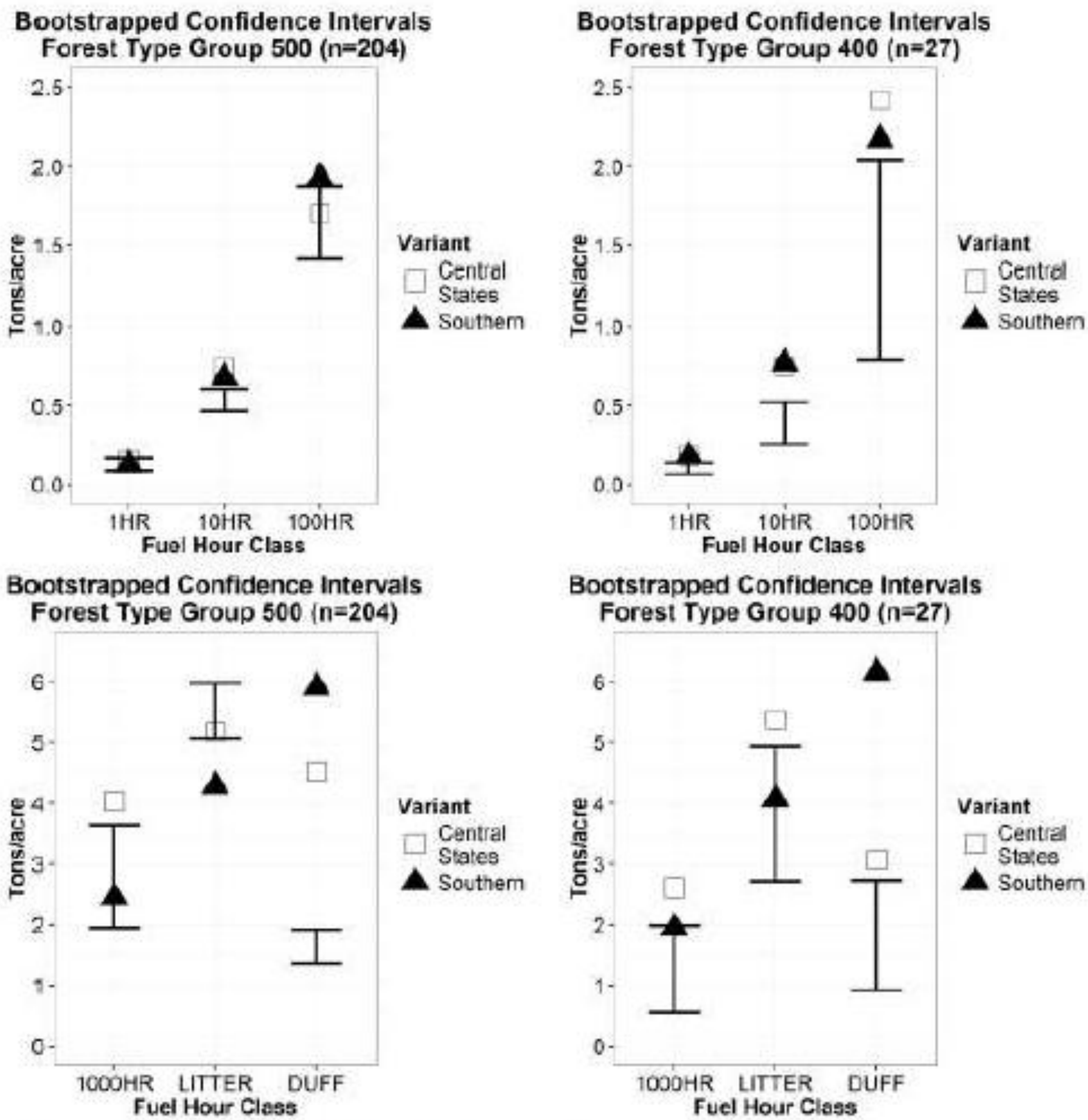

Figure 3. Default Central States (CS) and Southern (SN) variant FVS-FFE fuel loading values compared to FIA inventoried fuel loading for oak-pine (type group 400) and oak-hickory (type group 500) forest types in the Ozarks. Error bars represent ± 2 standard errors.

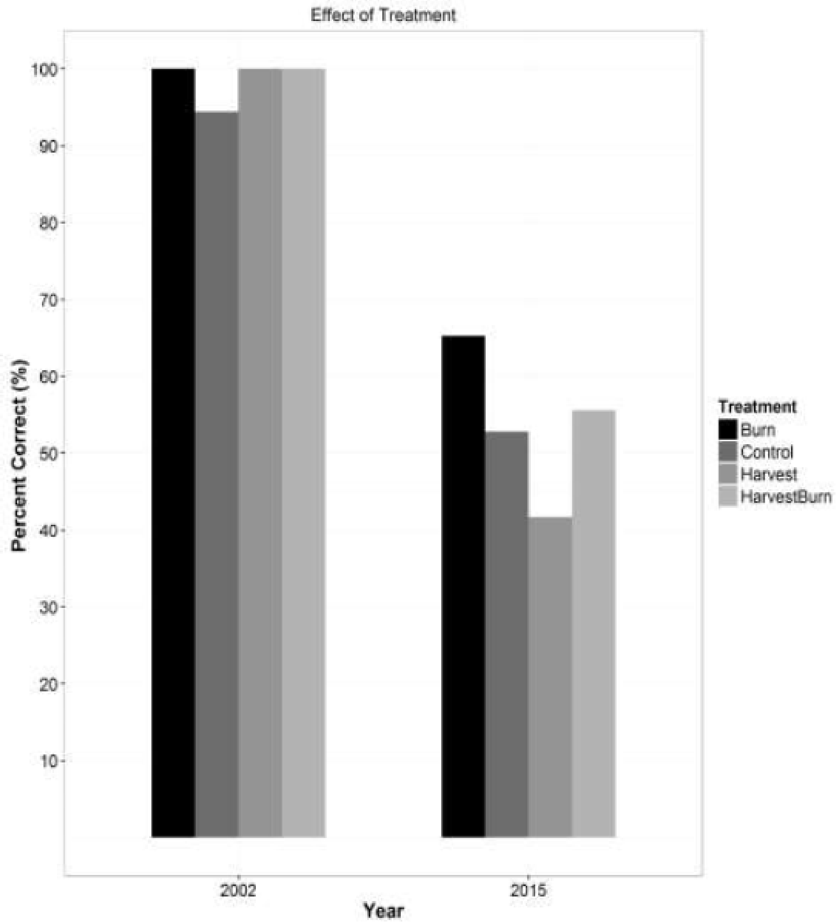

Figure 4. Percentages of stands classified into the correct fuel model at the beginning and end of a 14-year projection period.

Our comparison of FVS-FFE simulation results against empirical results at the end of a 14-year projection period showed that accuracy varied by fuel type and treatment (Figure 5). FVS-FFE consistently overpredicted duff compared to the empirical results for all silvicultural treatments, although treatments that included burning were the most accurate. In contrast, 1000 hour fuels were consistently underpredicted. In general, treatments with prescribed burning resulted in lower predictions of fuel loading from FVS-FFE and better corresponded to empirical data. The Control treatments resulted in overprediction of fuel loading for all fuel classes other than the 1000 hour fuels.

Despite the poor prediction of empirical fuel loading, FVS-FFE classified the fuel model correctly for approximately 65% of stands for the burn treatment and for approximately 40% of stands for the harvest treatment at the end of the 14 year period (Figure 4). Treatment significantly affected the classification of the fuel model ($p = 0.0427$).

Additional results from the site-scale study are presented in Ghilardi (2016) and Ghilardi et al. (2017).

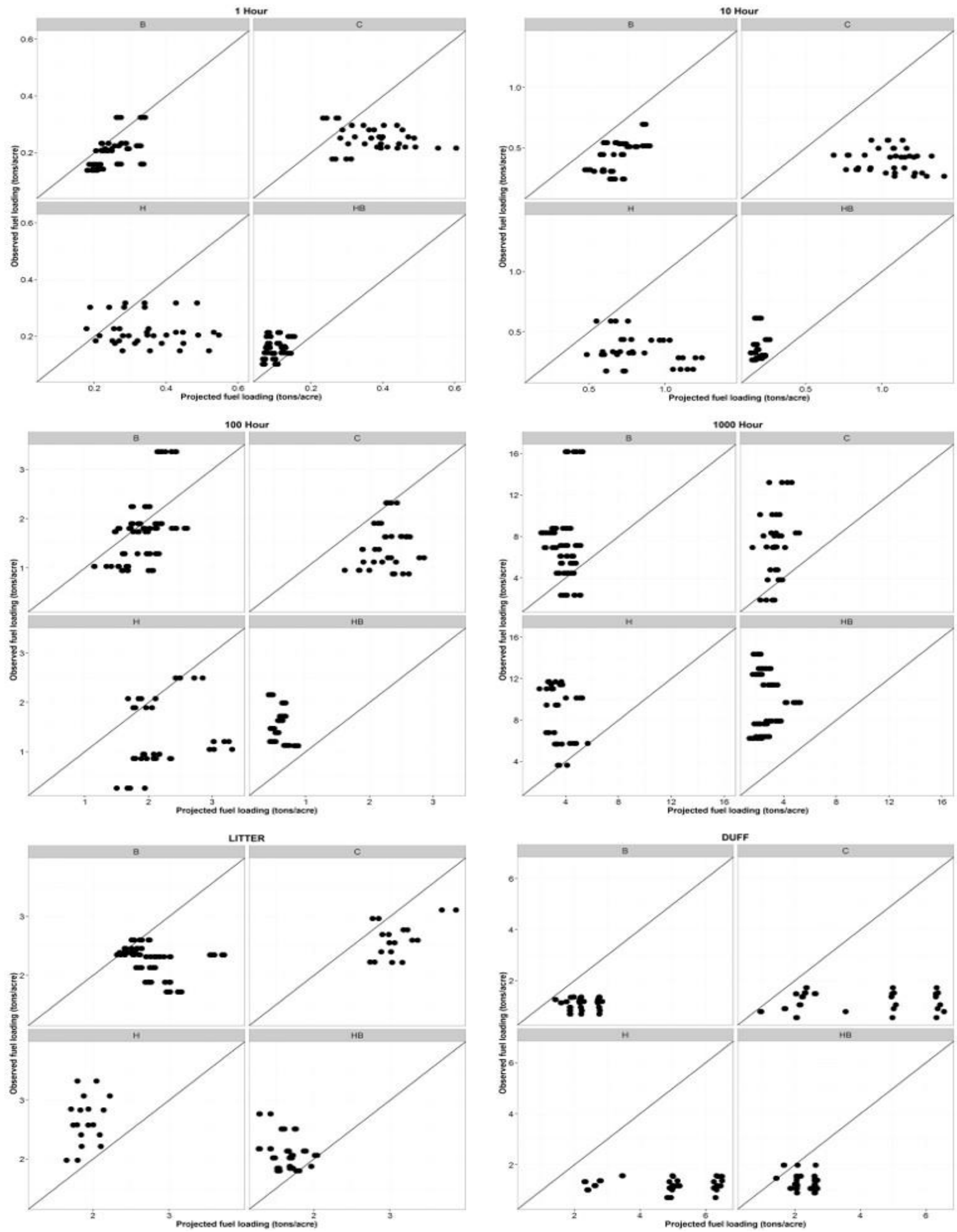

Figure 5. Comparison of mean FVS-FFE predicted fuel loading at the end of a 14-year simulation to empirical results by fuel type and treatment.

Landscape-scale study:

Overstory structure (tree density and basal area) in the first 40 years showed relatively little difference between the burn-only and no management scenarios (Figure 6). With prescribed burning there were more young trees (<30 yrs) and greater shortleaf pine regeneration with more burns. In scenarios including harvest (harvest only, and three harvest-burn combinations), tree densities generally increased throughout the simulations.

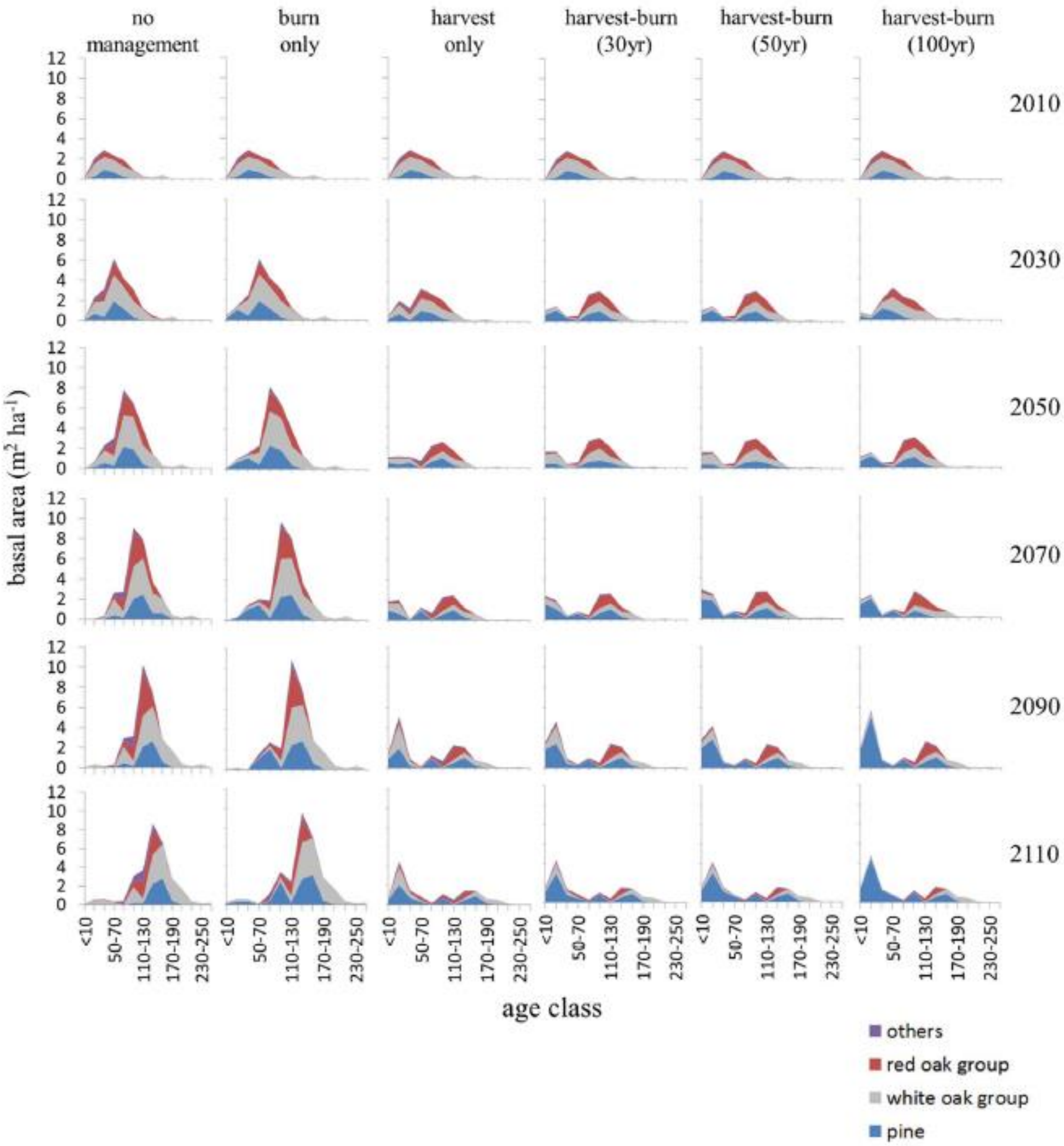

Figure 6. Basal area by age class of four species groups (colors) under six scenarios (columns) over a 100-year simulation period (rows).

Results from the landscape-scale modeling study suggest that neither a lack of management or prescribed burning alone, even over long periods of time, will effectively restore dominance of shortleaf pine nor restore current closed-canopy forests to a historical woodland condition (Figure 7). Under all four scenarios including harvest, percent canopy cover decreased from 88% to 80% in late 2020s, after which percent canopy cover remained in the woodland condition (40-80%). Despite different prescribed burn regimes in the four harvest scenarios, trajectories of percent canopy cover were highly similar.

A combination of harvest and prescribed burn can restore shortleaf pine woodland, with increasing burn frequency (higher costs) restoring the landscape quicker and tipping the landscape towards more pine dominated.

Additional results from the landscape-scale study are presented in Jin et al. (2018).

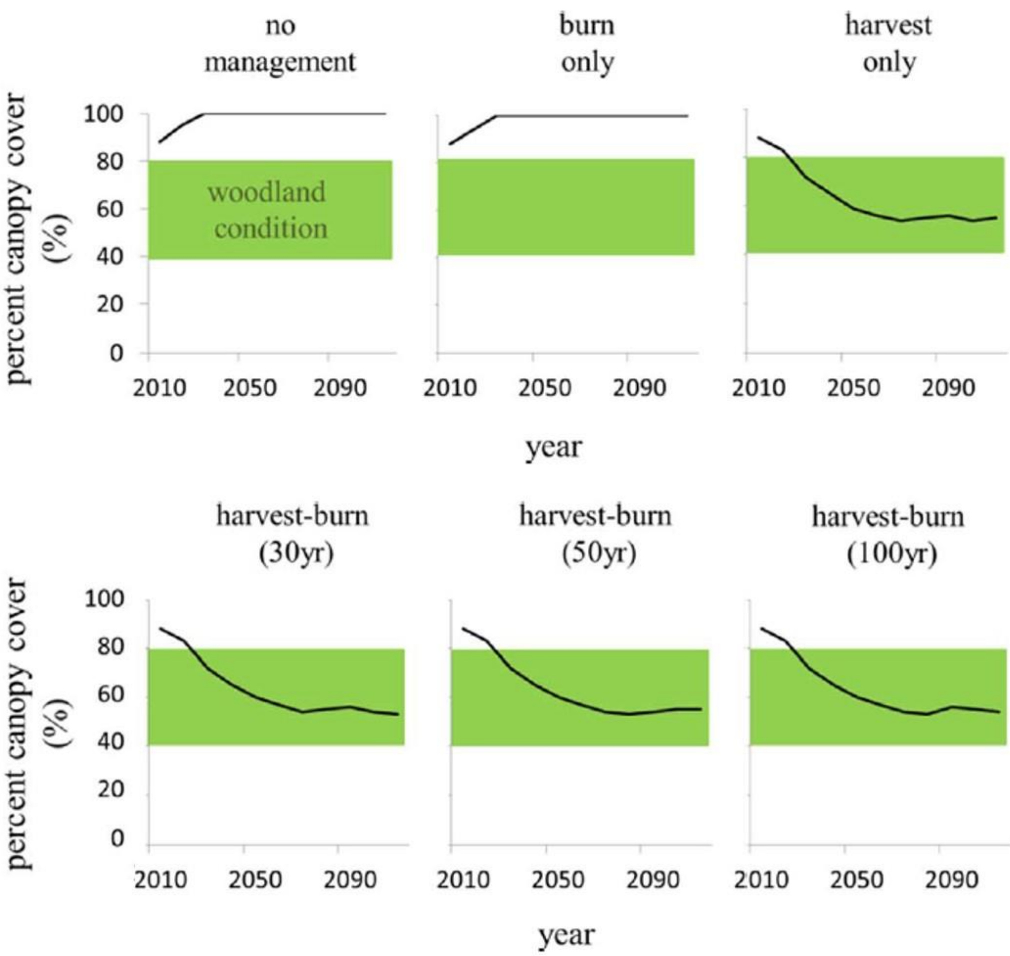

Figure 7. Projected percent canopy cover change over time under six management scenarios over a 100-year simulation period. Historically, percent canopy cover in the study area resembled a woodland condition, ranging from 40-80% (green band).

Conclusions (Key Findings) and Implications for Management/Policy and Future Research

Default values of fuel loading for the six fuel classes varied in their representation of field-based fuel loads within the Missouri Ozarks. Results from this work have been provided to FVS-FFE to update default fuel loads. Despite the variation in default fuel loads, the fuel models used by FVS-FFE were mostly correct at the beginning of the simulation period. Following short-term simulation, the fuel loading projects were not representative of field measurements. It is likely that exogenous events contributed to the poor accuracy in simulation. For example, 1000 hour fuels were consistently underpredicted by FVS-FFE. During the simulation/study period, the sites experienced widespread red oak decline that affected canopy trees and resulted in increased abundance of down wood by the end of the simulation period. Thus, modeling fuels through time is challenged by stochastic disturbance events that affect fuel inputs. Moreover, fuel loading values commonly have high levels of variation across the landscape and are poorly predicted by site or stand characteristics using empirical models. Additional research is warranted to develop mechanistic or process-based models for predicting patterns in fuel loading across local and landscape scales.

Landscape-scale simulation questions:

1) What landscape fuels treatment strategies are most effective at reaching restoration objectives for forest structure and composition?

Results from the landscape-scale modeling study suggest that prescribed burning alone, even over long periods cannot effectively restore dominance of shortleaf pine nor create a woodland tree structure from current closed-canopy forests. Tree mortality associated with prescribed burning is concentrated in small trees. Large overstory trees, which account for a substantial portion of basal area at both stand and landscape scales, rarely die from prescribed burning alone. Thus, the total basal area per hectare for prescribed burning alone was close to that under the no management scenario, and current closed canopy remained intact. Under all simulation scenarios that included harvest, percent canopy cover decreased and remained in the woodland condition after the late 2020s. Despite different prescribed burn regimes in the harvest scenarios, trajectories of percent canopy cover were highly similar.

2) How can landscape fuels treatment strategies maintain effectiveness over the short-term (<20 years), mid-term (20-50 years), and long-term (50-100 years)?

Harvest alone can reduce stand canopy cover to create woodland conditions. With combined prescribed burn and harvest, the total basal area had a similar pattern over time as that under harvest only scenario. However, shortleaf pine became more dominant with more burns, and the proportion of white oak would increase with less burning.

Taken together, these results indicate that harvesting is an important management treatment for creating woodland structure, and the prescribed burning regime will subsequently affect woodland composition through time.

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Appendix B – List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

Deliverable	Description	Delivery Dates
Poster	MS preliminary results	May 2016
Thesis	MS final results	December 2016
Presentations	PhD preliminary results	May 2016, 2017
Publications	MS publications	July 2017
Dissertation	PhD final results	July 2017
Regional workshop	Regional workshop will be given with Oak Woodlands & Forest Fire Consortium to share information with forest managers in Central Hardwood region	July 2017
Website	Results and maps on website	July 2017
Publications	PhD publications	July 2018

Poster –
Ghilardi, C., Knapp, B.O., Larsen, D.R., and He, H. 2016. Evaluation of the Fire and Fuels Extension of the Forest Vegetation Simulation within the Missouri Ozarks. Missouri Natural Resources Conference. February 3-5, 2016. Osage Beach, MO.

Ghilardi, C., Knapp, B.O., He, H., Larsen, D.R., and Kabrick, J.M. 2016. Evaluation of the Fire and Fuels Extension of the Forest Vegetation Simulation within the Missouri Ozarks. 20th Central Hardwood Forest Conference. March 28-April 1, 2016. Columbia, MO.

Thesis –
Ghilardi, C., 2016. Evaluation of the Fire and Fuels Extension (FFE) to the Forest Vegetation Simulator (FVS) within the Missouri Ozarks. M.S. Thesis. University of Missouri, Columbia, Missouri, School of Natural Resources.

Oral Presentations-
Jin, W., He, H.S., Knapp, B.O., Aguilar, F.X., Shifley, S.R., and Kabrick, J.M. 2017. Ecological-economic trade-offs of long term pine-oak woodland restoration in the Missouri Ozarks. Natural Areas Conference. October 10-12, 2017. Fort Collins, CO.

Ghilardi, C.R., Knapp, B.O., He, H.S., Larsen, D.R., and Kabrick, J.M. 2017. Evaluation of the Fire and Fuels Extension (FFE) of the Forest Vegetation Simulator (FVS) within the Missouri Ozarks. 2017 Forest Vegetation Simulator (FVS) e-Conference. February 28-March 2, 2017.

Publications –
Ghilardi, C.R, Knapp, B.O., He, H.S., Larsen, D.R., and Kabrick, J.M. 2017. Evaluation of the Fire and Fuels Extension to the Forest Vegetation Simulator within the Missouri Ozarks. In: Keyser, C.E. and Keyser, T.L. eds. Proceedings of the 2017 Forest Vegetation Simulator (FVS) e-Conference. e-Gen. Tech. Rep. SRS-224. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. pp 94-97.

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Jin, W., He, H.S., Shifley, S.R., Kabrick, J.M., Knapp, B.O., Aguilar, F.X. 2018 Ecological-economic trade-offs of long term pine-oak woodland restoration in a Central Hardwood Forest landscape (to be submitted to Ecological Applications).

Appendix C – Metadata (when applicable)